"TIN-FREE" LEADED BEARING BRONZE

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ABSTRACT

A study was made of the effect of small proportions of various elements on the distribution of lead in leaded bronzes containing more than 30 percent lead. The mechanical properties believed to be significant in the service of a bearing were determined at several different temperatures for leaded bronzes developed in the course of this investigation and which contained 30.5 to 40 percent lead, together with small amounts of sulphur, silicon, and zirconium. The mechanical properties of several commercial leaded bronzes containing 26 to 40 percent lead were also determined. Service tests were made on a set of connecting-rod and main bearings of the sulphur-silicon-zirconium leaded bronze installed in a Wright type J-5 airplane engine.

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I. INTRODUCTION

The development of greater power and higher speeds in internal-combustion engines and in other machines necessitates the use of bearing alloys with mechanical properties at elevated temperatures exceeding those of the usual white-metal bearing alloys in addition to the essential properties of any satisfactory bearing metal. Lead-copper aggregates, consisting of lead dispersed in a matrix of copper or a copper-base alloy, have shown promise and have had some application in meeting these increasing demands. In this report these lead-copper aggregates are referred to as leaded bronzes. Bronzes containing 25 to 28 percent or more lead have to a great extent replaced tin-base alloys in connecting-rod bearings of airplane engines.

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Commercial leaded bronzes of high lead content generally contain tin. The tin is added to prevent the agglomeration and segregation of lead particles and to strengthen the matrix of the alloy. The usual maximum lead content of commercial leaded bronzes prepared by ordinary foundry methods is about 28 percent. Segregation of lead is usually excessive in alloys containing 30 percent or more of lead.

The primary purpose of the work reported in this paper was to develop a leaded bronze of high lead content, containing no tin or other strategic metals,[1] which could replace the usual tin-base-bearing alloys in many fields of service. The investigation, which was sponsored by the War Department, comprised two phases, (1) a study of the effect of small proportions of various elements on the distribution of lead in leaded bronzes containing more than 30 percent lead, and (2) the determination of the characteristic mechanical properties of leaded bronzes containing 30.5 to 40 percent of lead, together with small amounts of sulphur, silicon, and zirconium. The mechanical properties of several commercial leaded bronzes containing from 26 to 40 percent lead were also determined.

Service tests were also made on a series of steel-backed bearings lined with one of the more promising of the alloys developed during the course of this investigation, namely, a copper-lead-bearing metal treated with sulphur, silicon, and zirconium. These service tests were made on bearings installed in a Wright type J-5 airplane engine which was run on an engine test block.

II. FACTORS AFFECTING THE DISTRIBUTION OF LEAD IN LEADED BRONZES

1. CONSTITUTION OF COPPER-LEAD ALLOYS

The solubility of lead in copper in the solid state is negligible. Recently, Claus [2] showed that copper-lead mixtures containing 37 to 38 percent lead are completely miscible above 950° C. A melt of this composition when cooled slightly below this temperature consists of a solid phase containing over 95 percent copper and a liquid phase which is relatively pure lead. Unless cooled very rapidly through the freezing range, the liquid phase of nearly pure lead coalesces into relatively large masses during the freezing and the aggregate at room temperature shows marked segregation of lead. The freezing of homogeneous melts containing less than 38 percent lead is similar to the example just given except that the temperature at which the relatively pure copper separates from the melt exceeds 950° C. in proportion to the decrease of the lead content below 38 per cent. Thus, in alloys containing the lower proportions of lead, there is formed during freezing a more continuous network of copper before the liquid phase becomes nearly pure lead and, as a consequence, the tendency toward segregation of lead is not so great in these alloys.

The problem is further complicated by the fact that alloys containing more than 38 percent lead, when melted, consist of two immiscible liquid phases and the lead is therefore already segregated even in the liquid phases before any restraining network of a solid phase can form.

[1] Roger Taylor, Strategic Raw Materials, Metals and Alloys, vol. 1, p. 5, 1929
[2] W. Claus, Zur Kenntnis des System Kupfer-Blei und verwandter heterogener Systems, Zeit. f. Metallkunde, vol. 23, no. 9, p. 264, September 1931.

2. COMPOSITION OF ALLOYS PREPARED

Suppression of lead segregation in lead-copper aggregates which are cooled rather slowly, as in sand castings, can sometimes be accomplished by the addition to the alloy of small proportions of certain elements. In order to determine the elements which are effective in this respect for leaded bronzes containing approximately 35 and 50 percent lead, a series of alloys of the compositions shown in table 1 was prepared.

TABLE 1.—*Compositions and casting temperatures of leaded bronzes with additions of elements to effect dispersion and distribution of lead*

Alloy	Copper[1]	Lead[1]	Added elements[1]	Percent	Casting temperature
	Percent	*Percent*			*°C.*
B	64	35	Tin	1	1,100 (2,010° F.)
C	49.5	49.5	___do___	1	1,100 (2,010° F.)
H	64	35	Manganese	1	1,100 (2,010° F.)
J	49.5	49.5	___do___	1	1,100 (2,010° F.)
L	61.5	33.5	___do___	5	1,100 (2,010° F.)
M	47.5	47.5	___do___	5	1,100 (2,010° F.)
N	64.5	34.5	Calcium	1	1,100 (2,010° F.)
P	49.5	49.5	___do___	1	1,100 (2,010° F.)
Q	63.5	34.5	___do___	2	1,100 (2,010° F.)
S	64.5	34.5	Barium	1	1,100 (2,010° F.)
T	49.5	49.5	___do___	1	1,100 (2,010° F.)
W	63	34	Magnesium	3	1,100 (2,010° F.)
X	64	34.5	___do___	1.5	1,100 (2,010° F.)
Y	49.5	49	___do___	1.5	1,100 (2,010° F.)
A-1	64.5	34.5	Aluminum	1	1,100 (2,010° F.)
B-1	49.5	49.5	___do___	1	1,100 (2,010° F.)
A-2	64.5	34.5	Nickel	1	1,100 (2,010° F.)
B-2	49.5	49.5	___do___	1	1,100 (2,010° F.)
A-3	64.4	34.6	Silicon	1	1,100 (2,010° F.)
B-3	49.5	49.5	___do___	1	1,100 (2,010° F.)
A-4	64.4	34.6	Zirconium	1	1,100 (2,010° F.)
B-4	49.5	49.5	___do___	1	1,100 (2,010° F.)
A-6	65	35	Lithium	0.05	1,100 (2,010° F.)
B-6	50	50	___do___	0.05	1,100 (2,010° F.)
A-8	64.5	34.5	Silicon-zirconium alloy	[2]1.5	1,100 (2,010° F.)
B-8	49.5	49.5	___do___	1.5	1,100 (2,010° F.)
A-9	64.5	34.5	Titanium	1	1,100 (2,010° F.)
B-9	54.5	44.5	___do___	1	1,140 (2,085° F.)
B-14	54.5	45	Sulphur	0.4	960 (1,760° F.)
B-17-1	54.5	44.5	{Sulphur Silicon-zirconium alloy	0.4 [2]1	}990 (1,815° F.)
B-19-0	54	44	{Sulphur Silicon-zirconium alloy	0.4 [2]1.5	}960 (1,760° F.)
B-22-0-9	54.5	44.5	{Sulphur Silicon-zirconium alloy	0.4 [2]0.5	}950 (1,740° F.)
B-23-0-9	53.5	44	{Sulphur Silicon-zirconium alloy	0.4 [2]2	}950 (1,740° F.)

[1] Nominal compositions.
[2] The silicon-zirconium alloy is a commercial product containing approximately 55 percent zirconium, 38 percent silicon, 5 percent iron, and small amounts of aluminum and carbon.

3. PREPARATION OF ALLOYS

Heats, 6 to 8 pounds each, of the desired compositions, melted in a gas-fired furnace in clay-graphite crucibles, were cast in green sand molds. The castings were cylindrical, 2½ inches long by 1¼ inches in diameter as shown in figure 1. (A few specimens were 3 inches by three fourths inch in diameter.) In each case, the metal was heated 100° to 125° C. (212° to 255° F.) above the desired casting temperature (table 1), thoroughly stirred while cooling to the casting

temperature and then poured. The heats were deoxidized by phosphorus-copper added shortly before casting.

Most of the elements added to influence the dispersion of lead were added directly to the melt. Some were added in the form of alloys or "hardeners", usually containing about 10 percent of the "addition" element alloyed with 90 percent copper, prepared beforehand in a high-frequency induction furnace. The elements added in this manner were titanium, nickel, silicon, zirconium, and silicon-zirconium alloy. Manganese was added as a 70–30 copper-manganese alloy. Sulphur was added both as roll sulphur and as lead sulphide.

4. METALLOGRAPHIC EXAMINATION AND DISCUSSION

The castings were sectioned longitudinally and polished for metallographic examination. Lead can be detected readily in an unetched polished copper matrix. Hence the specimens were examined in the
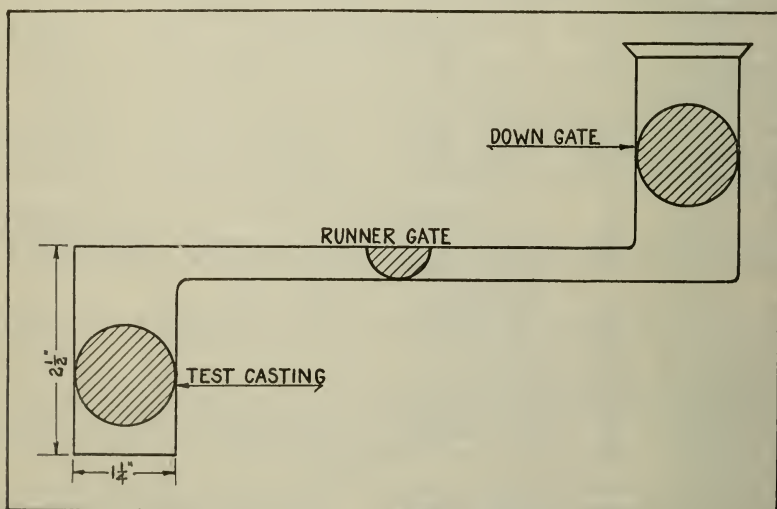

FIGURE 1.—*Form of casting for determining the effect of added elements on distribution of lead in leaded bronzes.*

unetched condition, since the metallographic study was primarily made to determine the manner in which lead was distributed.

The various "addition" elements, on the evidence given by the specimens examined, were grouped as follows:

1. Those which had a negligible effect in preventing segregation of the lead. The distribution of the lead in typical examples is shown in figure 2.

2. Those which aided in obtaining uniformity of distribution of the lead, but which did not prevent the lead from forming continuous envelopes around the grains of the copper-rich phase which thus destroyed the continuity of the matrix (fig. 3).

3. Those which prevented segregation and aided in dispersing the lead as discontinuous particles, a condition which favors continuity of the copper-base ground mass (fig. 4).

Obviously, the "addition" elements of group 1 are undesirable. Elements of group 2 may be considered as partially beneficial, but
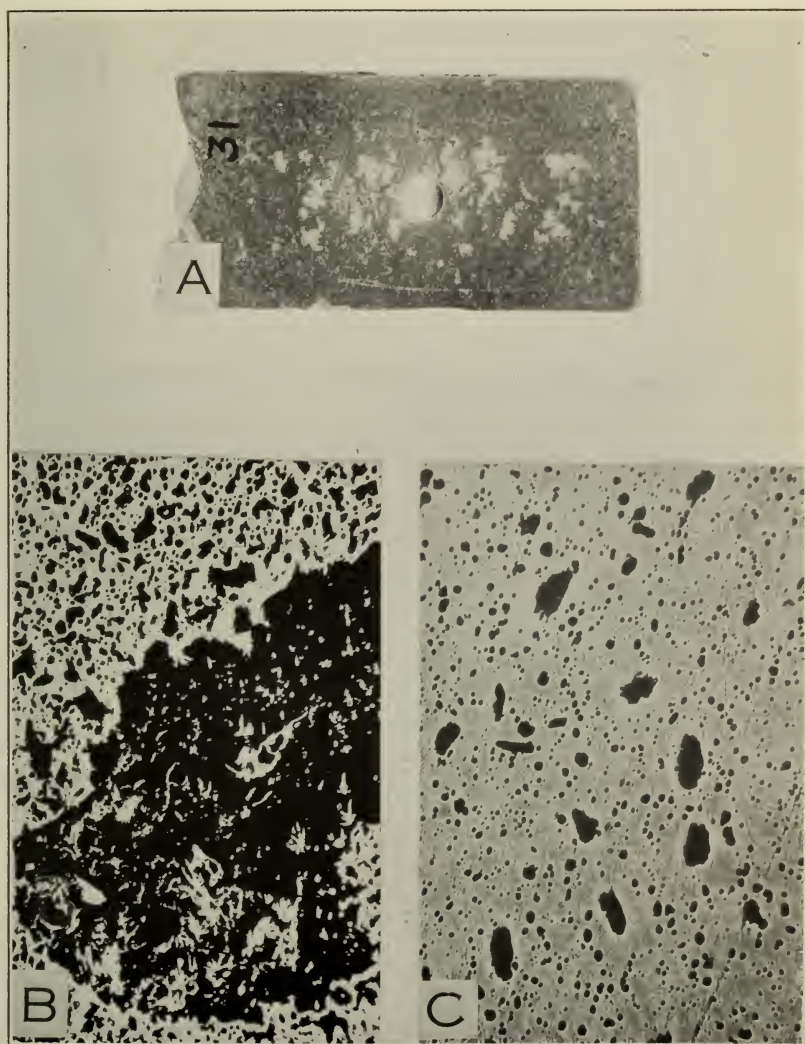
FIGURE 2.—*Typical structures of specimens in which additions were ineffective in preventing lead segregation.*

The heats from which these specimens were cast contained 45 percent lead. *A*, Lighter areas show typical appearance of segregated lead. × 1. *B*, Typical appearance of areas in region of heavy segregation of lead. Lead is represented by dark areas. × 50. Unetched. *C*, Typical appearance of "lead-poor" areas in regions free from segregation. Lead is represented by dark areas. × 50. Unetched.
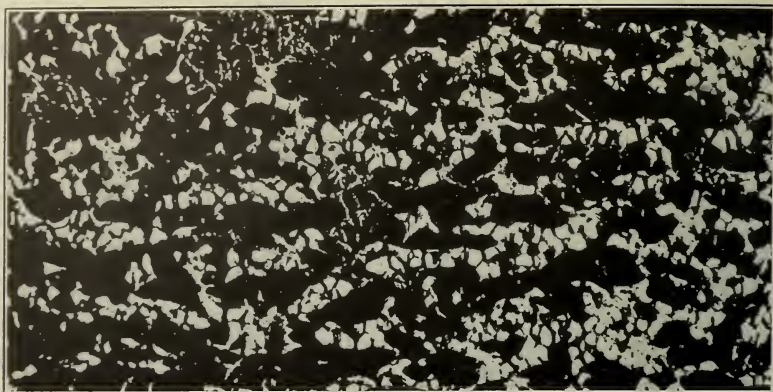
FIGURE 3.—*Microstructure of a bronze containing approximately 45 percent lead, 0.4 percent sulphur, and remainder copper, in which the lead, represented by the dark areas, was distributed uniformly, but in such manner as to break the continuity of the copper-base material, thus destroying its supporting effect.* × 50. *Unetched.*
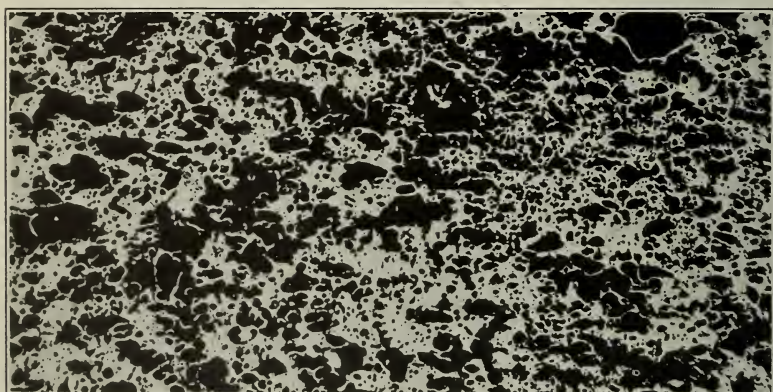

FIGURE 4.—*Structure of a bronze containing approximately 44 percent lead, 0.4 percent sulphur, 1.5 percent silicon-zirconium alloy, and remainder copper, showing the lead, represented by the dark areas, distributed as discontinuous areas, thus permitting a continuous copper-base matrix.* × 50. *Unetched.*
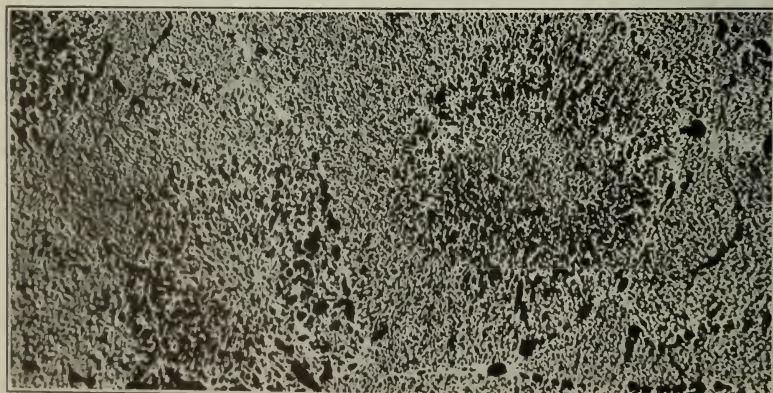

FIGURE 5.—*Microstructure of a bronze containing about 35 percent lead and 1 percent silicon showing the dispersion of the lead, represented by the dark areas, in an area of specimen which was free of lead segregation.* × 50. *Unetched.*
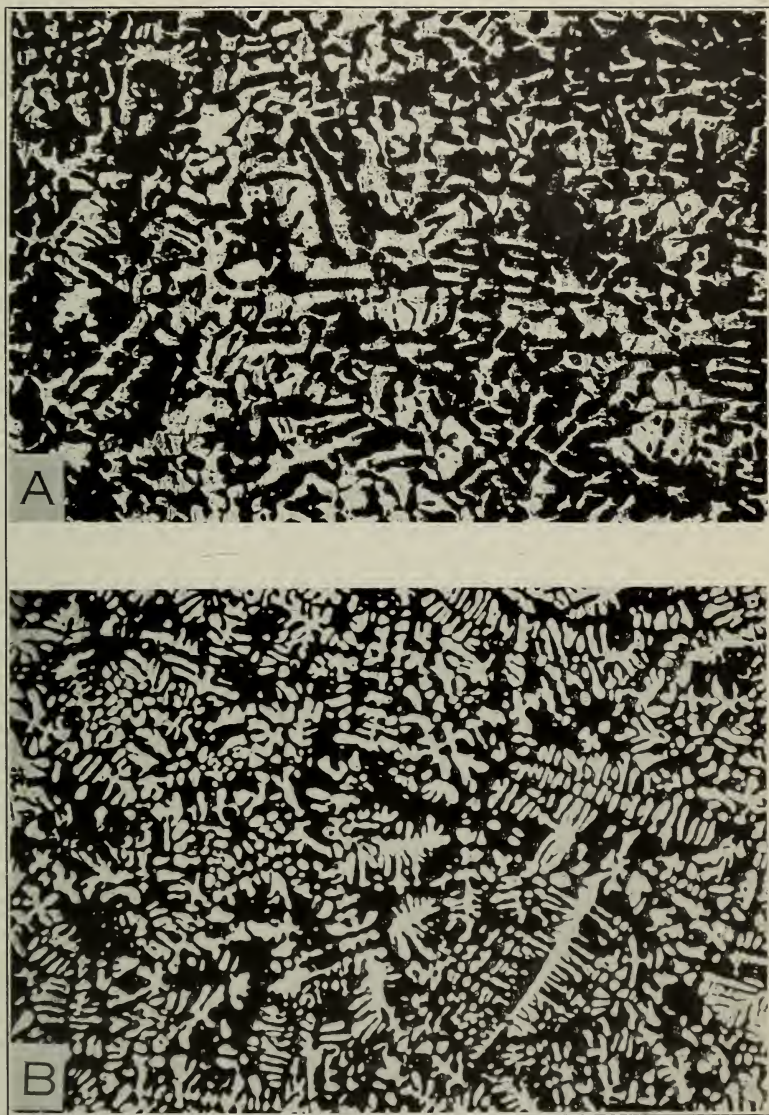
FIGURE 6.—*Microstructures of bronzes containing about 34.5 percent lead and different additions of calcium showing the dispersion of the lead, represented by dark areas.* × *50. Unetched.*

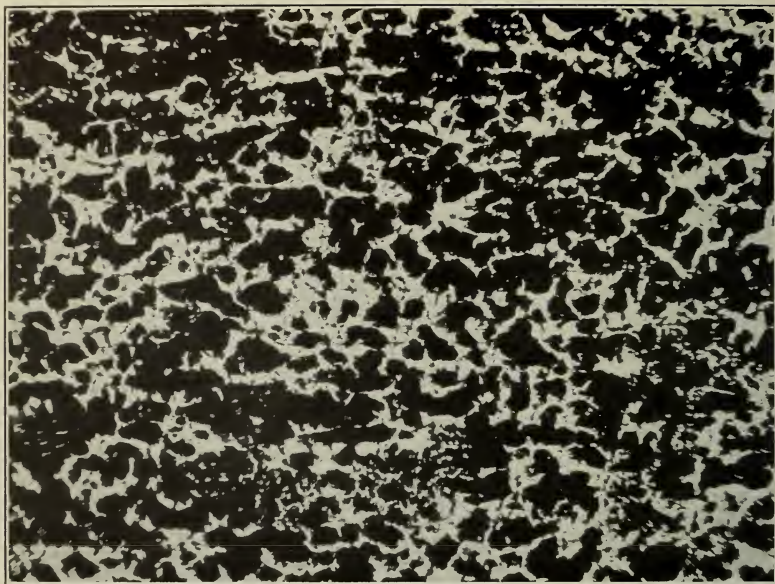*A*, 1 percent calcium. *B*, 2 percent calcium.

FIGURE 7.—*Microstructure of specimen containing about 55 percent copper, 45 percent lead, and 0.4 percent sulphur.* × 50.
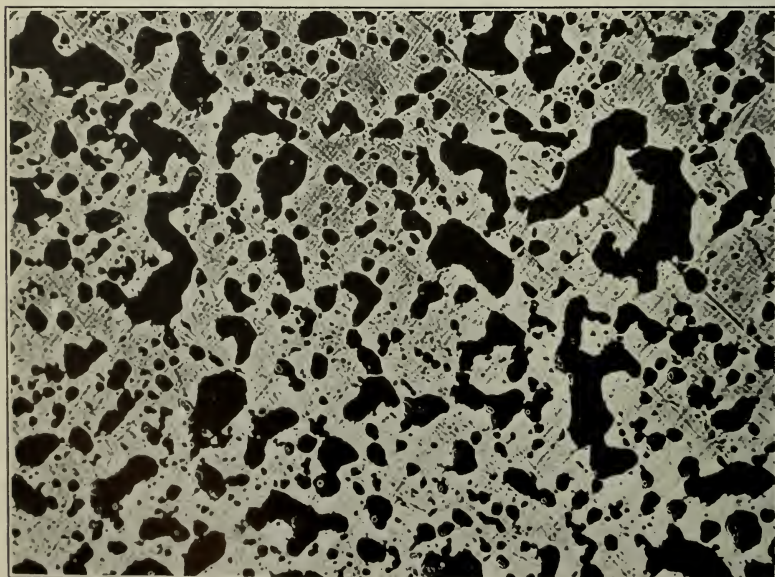
The lead is represented by the dark areas. Unetched.

FIGURE 8.—*Microstructure of casting containing about 64.5 percent copper, 34.5 percent lead, and 1 percent zirconium.* × 50.

The lead is represented by the dark areas. Unetched.

cannot be considered entirely satisfactory on account of loss of continuity and strength of the copper-rich matrix. The most effective and desirable addition elements are those of group 3. Obviously, a wide variety of microstructures can be obtained in high-lead bronzes by suitable variations in the casting conditions. The results here discussed refer only to specimens cast under the conditions described.

The "addition" elements which, in the amounts used in this work, had no marked beneficial effect on the distribution of lead in leaded bronzes containing 35 percent or more lead included the following: Lithium, 0.05 percent; magnesium, 1.5 and 3 percent; aluminum, titanium and tin, 1 percent each; manganese, 1 and 5 percent; and nickel, 1 percent. Although the addition of silicon was not entirely beneficial, since considerable segregation of lead was observed at the bottom of the casting, its use did result in unusual dispersion of the lead in the areas free of segregation (fig. 5).

Either calcium or sulphur aided in distributing the lead uniformly, but failed to prevent the formation of continuous lead envelopes around the copper-rich grain (fig. 3). Although a few small segregated areas were observed in specimens containing approximately 34.5 percent lead, treated with 1 and 2 percent calcium, respectively, they were not of such magnitude as to be considered serious. These specimens showed exceptional uniformity in the distribution of the lead as shown in figure 6. The melts treated with calcium drossed very severely on account of the rapidity with which calcium oxidizes. The alloy containing 2 percent of calcium was very brittle.

The use of sulphur for preventing segregation in leaded bronzes has long been known.[3] The effectiveness of sulphur has been attributed to its ability to decrease the range of immiscibility of copper and lead in the liquid state.[4] A sand-cast specimen containing approximately 55 percent copper, 45 percent lead, and 0.4 percent sulphur showed unusually uniform distribution of the lead (fig. 7).

Zirconium and barium added separately, promoted the dispersion of lead in the manner described under group 3. Castings which contained 34.5 percent lead and 1 percent zirconium were free of lead segregation. Castings prepared from a melt of similar lead content treated with 1 percent barium showed a few small, almost negligible, areas of segregation. Although the barium was added as metallic barium sheathed in copper to prevent oxidation, it "burned out" to some extent during heating and caused excessive drossing. The lead distribution in these specimens, as shown in figures 8 and 9, was fairly satisfactory. However, neither zirconium nor barium was effective in preventing segregation in castings made from bronze containing 49.5 percent lead.

Although the addition of sulphur resulted in very uniform distribution of the lead, its use was not entirely satisfactory because it destroyed the continuity of the copper matrix (fig. 7) which caused the bronze castings to have low compressive strength. Zirconium and barium, on the other hand, had shown a marked ability to disperse the lead in bronzes containing up to 35 percent lead. It

[3] A. Allan, Jr., The Patent Controversy Over Bearing Metals (9th and 11th papers), Metal Industry (N.Y.), vol. 9, pp. 155 and 295, 1911.
[4] W. M. Corse, Bearing Metals and Bearings, Am. Chem. Soc. Monograph Series No. 53, Chemical Catalog Co., New York, N.Y.

would seem reasonable, therefore, that either or both of these elements when added with sulphur to a high-lead bronze should give the desired type of lead distribution. Barium proved to be unsatisfactory, because of the rapidity with which it oxidized and combined with sulphur to form a slag which largely eliminated both added elements. The present cost and availability of metallic zirconium makes its use for other than experimental purposes almost prohibitive. For further experimental work, therefore, a commercial alloy of zirconium and silicon was substituted. This alloy contained about 55 per cent zirconium, 38 percent silicon, 5 percent iron, and less than 2 percent aluminum. The presence of silicon in this alloy seemed desirable. Silicon itself did not prevent segregation, but because of its dispersive power as illustrated in figure 5, there was reason to expect that it would be useful in combination with either zirconium or zirconium and sulphur. Several combinations of these elements were used as additions to leaded bronze containing 35 and 45 percent lead. The sulphur was varied from 0.1 to 0.5 percent and the silicon-zirconium alloy from 0.5 to 2 percent. It was found that the best distribution and dispersion of the lead was obtained by the use of the combined addition of 0.4 percent sulphur and 1 to 1.5 percent silicon-zirconium alloy. The effect of additions of 1 and 1.5 percent silicon-zirconium alloy on the microstructures of specimens containing approximately 54 percent copper, 45 percent lead, and 0.4 percent sulphur are shown in figures 10 and 4, respectively.

III. MECHANICAL PROPERTIES

1. PREPARATION OF ALLOYS

The mechanical properties, believed to be of significance in the service of a bearing, were determined on a series of sulphur-silicon-zirconium-treated copper-lead alloys.[5] The alloys containing these addition elements showed the best dispersion of the lead. In order to study the effect on the mechanical properties of various percentages of silicon-zirconium-alloy additions, alloys of the compositions shown in table 3 were prepared as 80-pound heats in a high-frequency induction furnace. This furnace was used primarily for convenience.

After the various constituents of each alloy were added, the melt was heated sufficiently to insure thorough alloying. The heat was then allowed to cool to approximately 950° C. (1,740° F.) and cast in closed green sand molds in shapes as later described under the discussion of each specific test.

2. APPARATUS AND TESTS

(a) RESISTANCE TO WEAR

The resistance to wear was determined on the Amsler universal wear testing machine modified for the testing of soft alloys as described in a previous publication.[6] The test specimens, which were cast as "tires" on the peripheries of steel rings, were run against reference specimens of SAE 1045 steel treated to a hardness of 240

[5] H. K. Herschman and J. L. Basil, Copper-lead Alloys, U.S. Patent No. 1895261, 1932.
[6] H. K. Herschman and J. L. Basil, Mechanical Properties of White Metal Bearing Alloys at Different Temperatures, Proc. ASTM, vol. 32, pt. 2, p. 536, 1932.
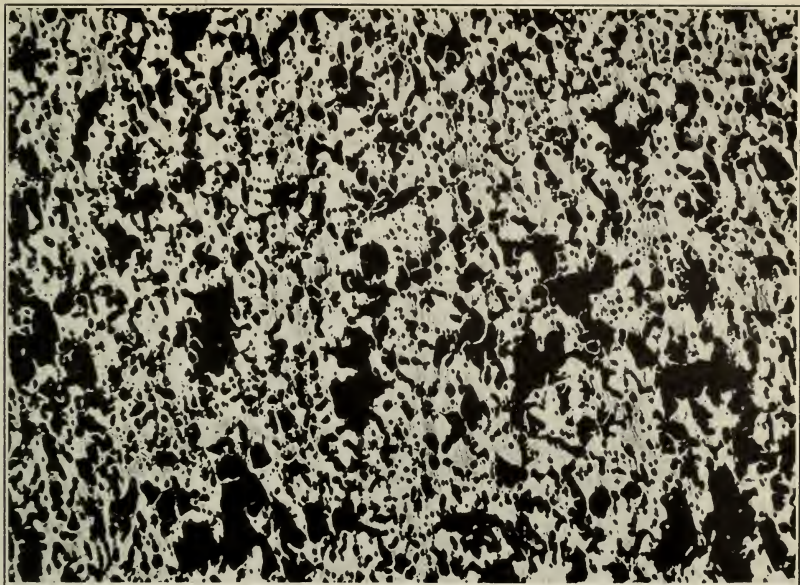
FIGURE 9.—*Microstructure of leaded bronze casting containing approximately 64.5 percent copper, 34.5 percent lead, and 1 percent barium.* × 50.

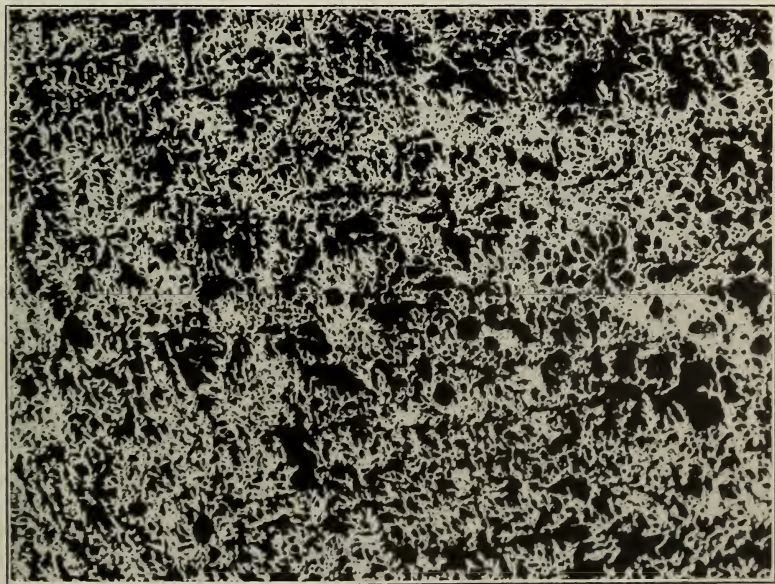The lead is represented by the dark areas. Unetched.

FIGURE 10.—*Microstructure of leaded bronze casting containing approximately 54 percent copper, 44.5 percent lead, 0.4 percent sulphur, and 1 percent silicon-zirconium alloy.* × 50.

The lead is represented by the dark areas. Unetched.

Brinell. Pressure was obtained at the area of contact between the specimens by applying a load of 10 pounds on the steel reference specimen. A stream of kerosene was directed on the test specimen near its area of contact with the reference specimen to provide partial lubrication and to cool the specimens. Tests were made at approximately 20° C. only.

The wear-resistance tests were made on commercially available leaded bronzes of high lead content[7] and on alloy B–21[8] of the compositions shown in table 2. The thickness of the bronze layer or "tire" cast on the steel back, after "finish-machining", did not exceed 0.015 inch.

TABLE 2.—*Compositions of commercially available leaded bronzes and of sulphur-silicon-zirconium-treated leaded bronze used in wear tests*

Specimen No.	Copper	Lead	Tin	Other constituents
	Percent	*Percent*	*Percent*	*Percent*
1–53 [1]	70	30	(2)	
P–6 [1]	70	24	6	
76–24 [1]	76	24	(2)	
60–40	[1] 61	[3] 39.1	(2)	
70–30	[1] 65.5	[3] 34.6	(2)	
1–70 [4]	69.3	30.59	--------	0.11 nickel and zinc.
72–5 [4]	69.46	28.48	1.78	.28 nickel and zinc.
75–4 [4]	68.23	26.20	4.96	.61 nickel and zinc.
B–21–1 [3]	66.5	31.5	--------	{Silicon-zirconium alloy 1.5.[1] {Sulphur 0.4.[1]

[1] Nominal compositions.
[2] Tin not reported.
[3] Determinations made by J. A. Scherrer, Bureau of Standards.
[4] Analysis made by The Bohn Aluminum & Bronze Co., Detroit, Mich.

(b) COMPRESSIVE STRENGTH

The apparatus and procedure for making compression tests were identical with those described in a previous publication.[9] The tests were made at approximately 20°, 100°, 150°, 200°, and 250° C. (68°, 212°, 300°, 390°, and 480° F.). The loads were applied in increments of 100 pounds, this increment being equivalent to an increase in stress of 500 lbs./in.². The speed of the crosshead of the machine was approximately 0.04 inch per minute. This low rate of speed was used as it permitted closer regulation of loading than would have been possible with the next higher speed available on the machine used.

The compression test specimens were made of only the five alloys listed in table 3. Alloys B-14, B-22, B-17, and B-21 (table 3) were prepared as castings five eighths inch in diameter by 4 inches long and alloy "C" (table 3) was purchased in the form of bars three fourths inch in diameter by 12 inches long. The "finish-machined" specimens were 0.505 inch diameter by 1 inch long.

Table 3.—*Composition of leaded bronzes prepared for compression, single blow charpy, impact and pounding tests* [1]

Heat designation	Copper	Lead	Silicon-zirconium alloy [1]	Sulphur [1]	Antimony
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
B-14	[2] 59. 3	40. 3		0. 4	
B-22	[2] 57. 4	41. 7	0. 5	. 4	
B-17	65. 4	33. 2	1. 0	. 4	
B-21-2	[2] 62. 1	36. 0	1. 5	. 4	
"C" [3] [4]	73. 75	26. 0			0. 25

[1] Amounts added to the heats.
[2] Copper determined by difference.
[3] Commercial leaded bronze.
[4] Pounding tests were not made on alloy "C."

(c) SINGLE-BLOW IMPACT VALUE

The single-blow impact resistance was determined with a Charpy impact machine of 224.1 foot-pound capacity. The tests were made at 20°, 100°, 150°, 200°, and 250° C. (68°, 212°, 300°, 390°, and 480° F.). The specimens tested above room temperature were heated in an electric muffle furnace, held at temperature for 15 minutes, then transferred to the machine and tested. Not more than three seconds were required for the last step. The heat loss during transference has been previously found to be negligible.[10] The specimens as cast were ⅝-inch square by 4 inches long. The "finish-machined" specimen conformed with the design recommended for the Charpy impact test in the Proposed Method for Impact Testing of Metallic Materials of the American Society for Testing Materials.[11]

(d) RESISTANCE TO POUNDING

The apparatus and the procedure for the pounding tests have been described in a previous publication.[12] Tests were made at 20°, 100°, 150°, 200°, and 250° C. (68°, 212°, 300°, 390°, and 480° F.). The cylindrical specimens, 0.394 inch in diameter by 0.985 inch long (10 by 25 mm), were machined from castings five eighths inch in diameter by 4 inches long.

3. RESULTS AND DISCUSSION

(a) RESISTANCE TO WEAR

The results of the wear tests are shown graphically in figure 11. Alloys B-21-1, 70-30, P-6, and 75-4 (table 2) had about the same rates of wearing after the "wearing-in period"; that is, after the first 10,000 to 20,000 revolutions. Alloys 75-4 and P-6 contained approximately the same amounts of lead and about 5 and 6 percent tin, respectively. The former also contained small proportions of nickel and zinc. Alloy 70-30 contained about 34.5 percent lead as compared with 31.5 percent in alloy B-21-1. Alloy 72-5, which contained about 28.5 percent lead, 1.75 percent tin, and a small percentage of nickel and zinc had a perceptibly higher rate of wear than the four alloys just considered. Specimens 1-53, 76-24, 1-70, and 60-40 (table 2) which were reported by the manufacturers to contain only

[10] G. Willard Quick, The Resistance to Impact of Rail Steels at Elevated Temperatures, B.S. Jour. Research, vol. 8 (RP409), p. 191, 1932.
[11] Proc., Am. Soc. Testing Materials, vol. 26, pt. 1, p. 553, 1926.
[12] See footnote 6, p. 596.

copper and lead, the latter element in amounts varying from 24 to 40 percent, had comparatively high rates of wear.

(b) COMPRESSIVE STRENGTH

The relation of stress to strain in compression at the various test temperatures for each of the alloys listed in table 3 is shown in figures 12, 13, 14, 15, and 16.

By using the least count of the extensometer as the criterion for the "departure from a straight line",[13] it was possible to determine
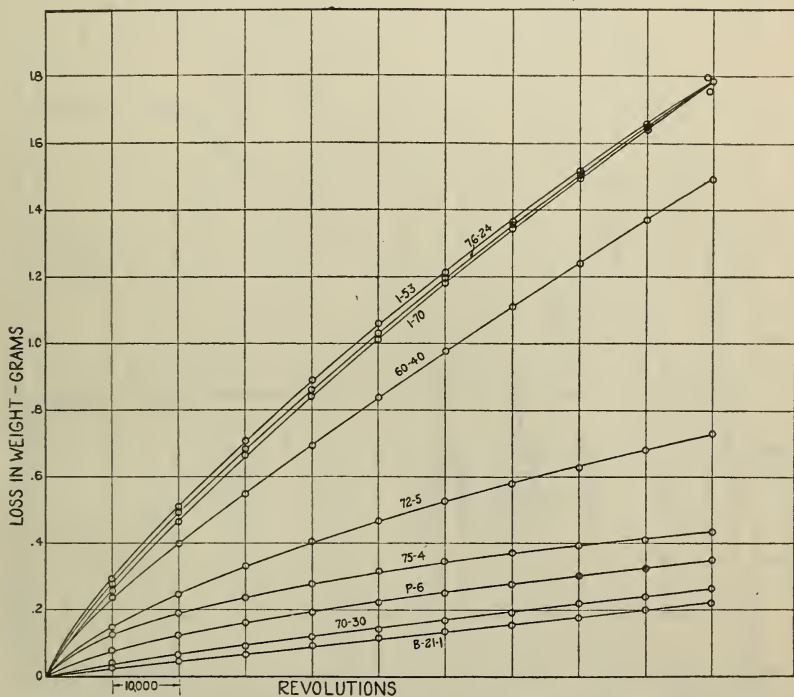

FIGURE 11.—*Relation between wear, as determined by loss of weight, and revolutions for leaded bronze bearing alloys tested on Amsler wear testing machine.*

The bronzes were cast on the peripheries of steel rings. All specimens were prepared in commercial foundries.
All alloys were tested against SAE No. 1045 steel heat-treated to give a Brinell hardness number of 240. The numbers on the curves are the specimen numbers listed in the table of compositions (table 2).

approximately the limits of proportionality of stress and strain at room temperature (figs. 12 to 16, inclusive). This determination became increasingly difficult and questionable, however, as the temperature of test increased, particularly for alloys B-14 and B-22. Hence, in order to show graphically the effect of temperature, an arbitrary value for strain was selected, namely, 0.3 percent, which was considered to represent the relative yield strength.[14] The stresses

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[13] Discussion by L. B. Tuckerman of paper by R. L. Templin, "The Determination and Significance of the Proportional Limit in the Testing of Materials", Proc. Am. Soc. Test. Mats., vol. 29, pt. 1, p. 538, 1929.
[14] ASTM tentative specification E-8-32T, vol. 32, pt. 1, p. 955.

necessary to produce deformations of 0.3 percent as determined from figures 12 to 16 are shown in figure 17.

The results of the compression tests indicated that alloy B-21-2 (table 3) which was treated with sulphur and silicon-zirconium alloy and contained 36 percent lead, was capable of sustaining loads comparable with those sustained by the commercial alloy "C", which contained only 26 percent lead.   Alloy B-21-2 had at 100° C. (212° F.)
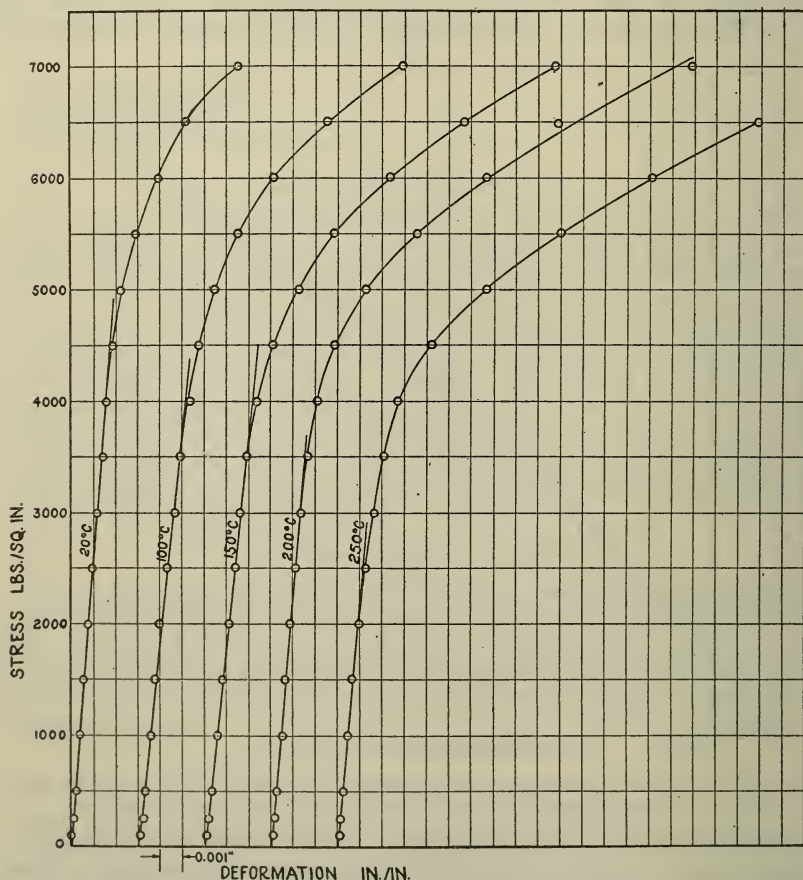

FIGURE 12.—*Stress-strain relation in compression tests at various temperatures for commercial alloy "C" (copper, 73.75 percent; lead, 26 percent; and antimony 0.25 percent).*

Each plotted point represents an average of two determinations.

a yield strength slightly higher than that determined at room temperature.   This was unusual and the results were checked with specimens of similar composition prepared from another heat.   The results although not included in this report, verified the increase shown in figure 17.   A few preliminary experiments also indicated that specimens of this composition after being heated at 90° to 100° C. for a period of 15 hours and then cooled to room temperature, possessed

higher compressive strength at room temperature than before being treated, which indicates that this alloy may be adaptable to age hardening treatments.   Alloys B-17, B-22, and B-14, which contained 0.4 percent sulphur and silicon-zirconium alloy up to 1 percent, had only about half the compressive strength of alloy B-21-2 treated with
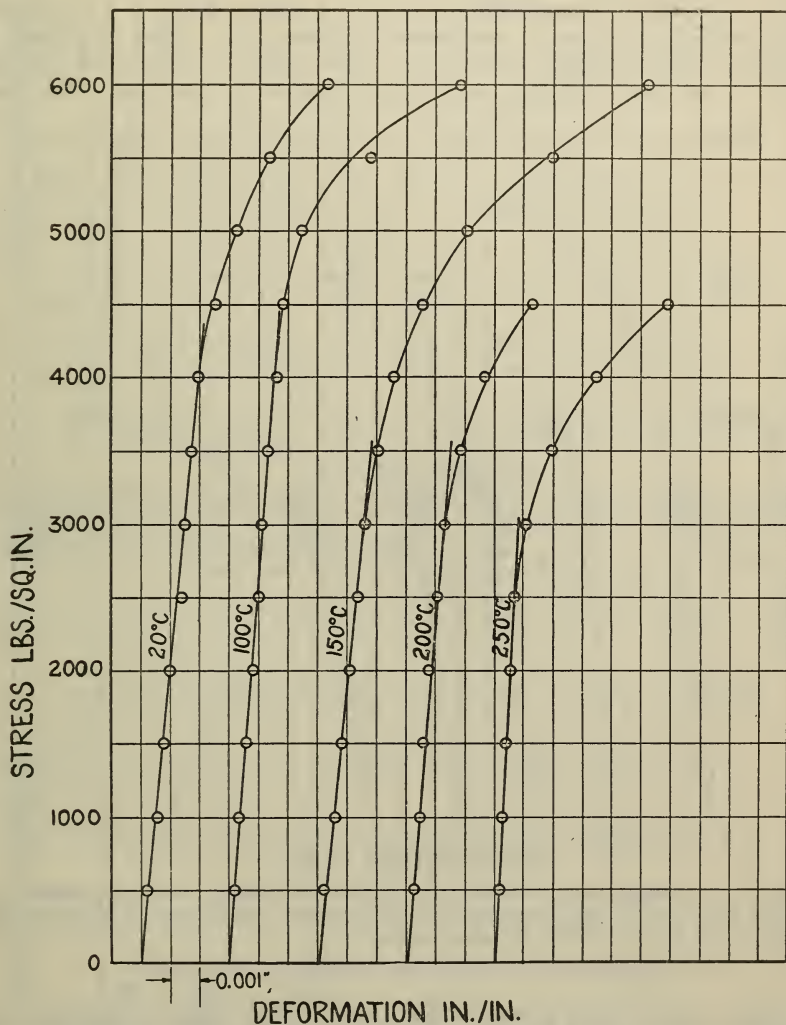

FIGURE 13.—*Stress-strain relation in compression tests at various temperatures for alloy B-21-2 (copper, 61.2 percent; lead, 36 percent, treated with 0.4 percent sulphur and 1.5 percent silicon-zirconium alloy).*

Each plotted point represents an average of two determinations.

0.4 percent sulphur and 1.5 percent silicon-zirconium alloy, and alloy "C", a commercial leaded bronze containing 0.25 percent antimony. Particularly to be noted (fig. 17), is the difference between the effect of the addition of 1.5 percent of silicon-zirconium alloy in alloy B-21-2 and the effect of the addition of 1 percent of silicon-zirconium alloy

in alloy B-17.   The slightly greater addition of silicon-zirconium alloy resulted in a marked increase in yield strength of the leaded bronze at all temperatures up to 250° C.

(c) SINGLE-BLOW IMPACT RESISTANCE

The results of Charpy impact tests on alloys B-14, B-17, B-21-2, B-22, and "C" (table 3) are shown in figure 18.   Alloy "C" had a relatively high impact resistance.   This may be accounted for, in part, by the fact that the proportion of lead in this alloy was con-
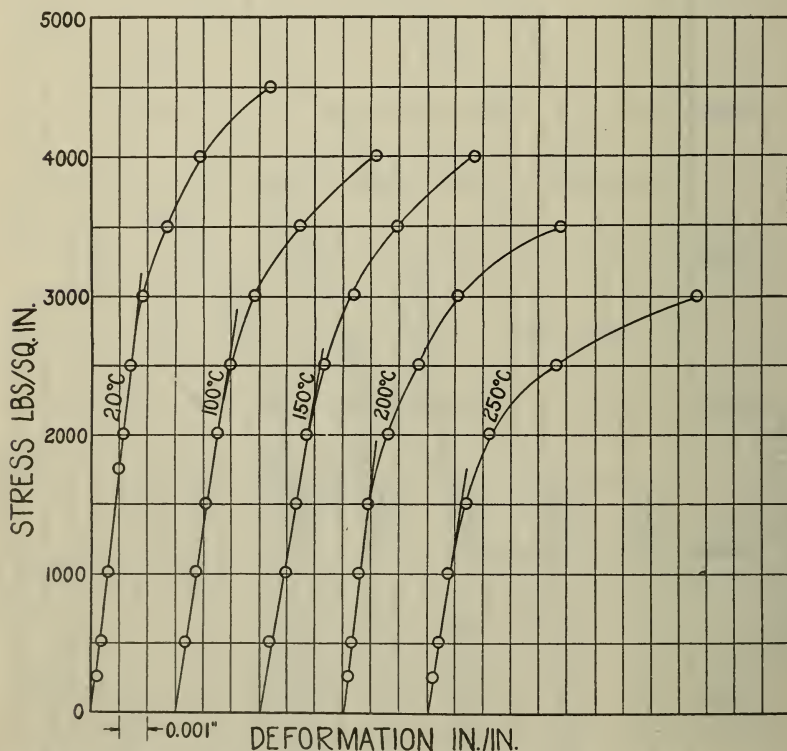

FIGURE 14.—*Stress-strain relation in compression tests at various temperatures for alloy B-17 (copper, 65.4 percent; lead, 33.2 percent, treated with 0.4 percent sulphur and 1 percent silicon-zirconium alloy).*

Each plotted point represents an average of two determinations.

siderably lower than in the other alloys.   The impact resistance of B-21-2, appeared to be only slightly affected by temperature.

(d) RESISTANCE TO POUNDING

The pounding tests measured the deformation of the specimens previously described, resulting from repeated blows from a 2-pound hammer or tup falling freely through a distance of 2 inches.   Figure 19 shows the relationship at 20°, 100°, 200°, and 250° C. (68°, 212°, 390°, and 480° F.) of the number of blows of the hammer to the resulting deformation for alloys B-14, B-22, B-17, and B-21-2 listed in
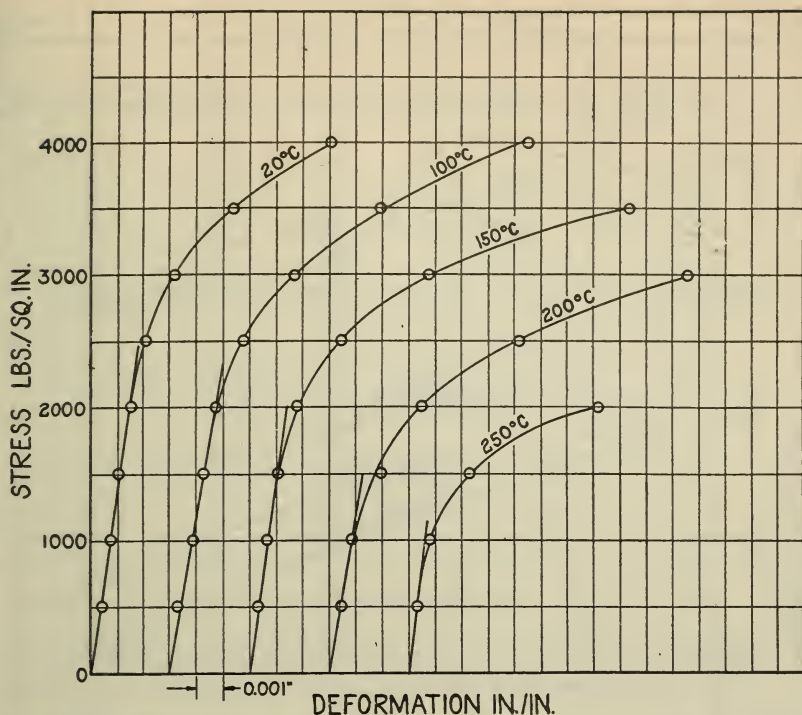
FIGURE 15.—*Stress-strain relation in compression tests at various temperatures for alloy B-22 (copper, 57.4 percent; lead, 41.7 percent, treated with 0.4 percent sulphur and 0.5 percent silicon-zirconium alloy).*

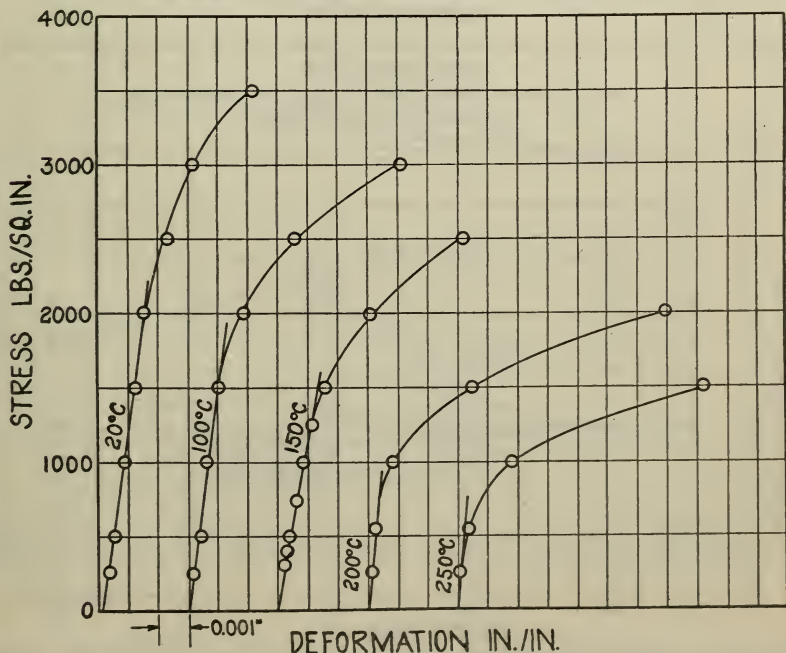Each plotted point represents an average of two determinations.

FIGURE 16.—*Stress-strain relation in compression tests at various temperatures for alloy B-14 (copper, 59.3 percent; lead, 40.3 percent and treated with 0.4 percent sulphur).*

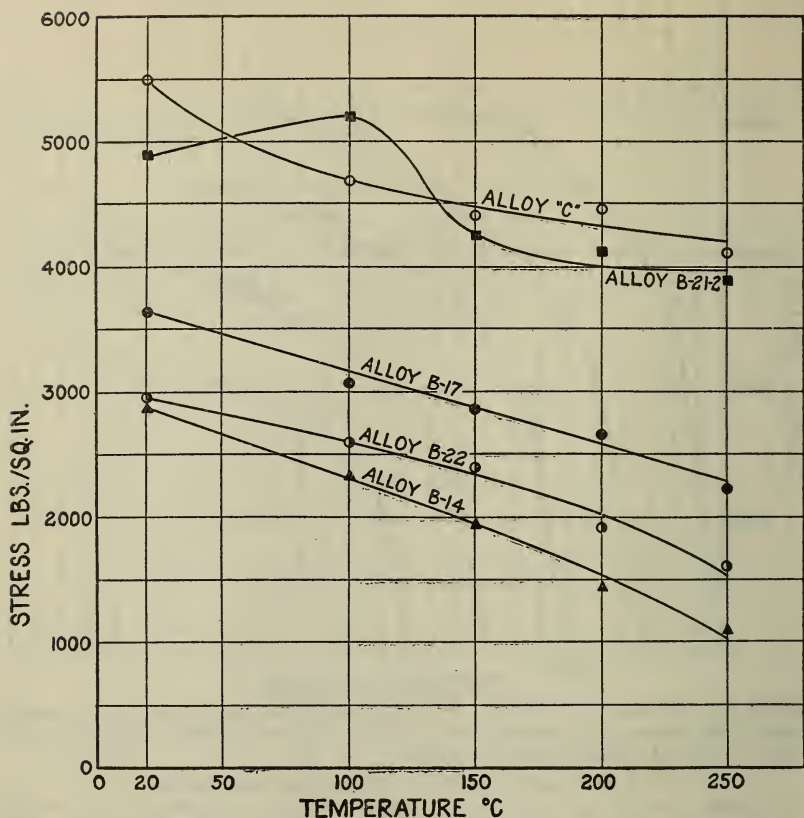Each plotted point represents an average of two determinations.

FIGURE 17.—*Relation of compressive stress producing 0.3 percent deformation to temperature of test.*

Each plotted point represents an average of two determinations.
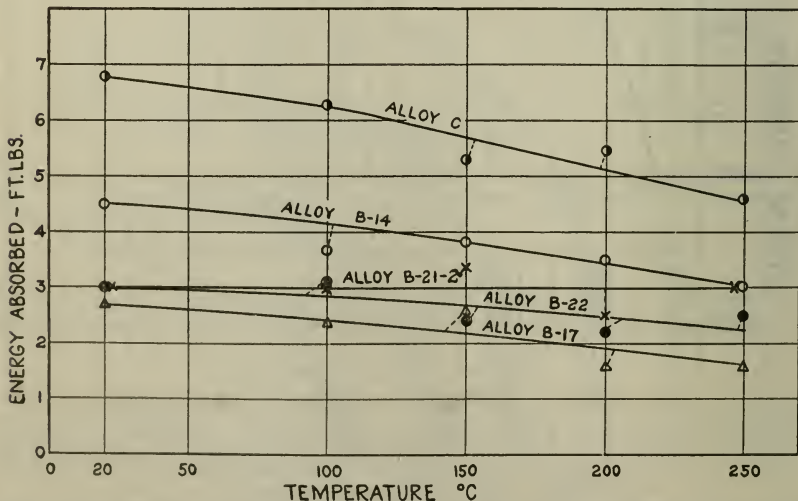Compositions given in Table 3.

FIGURE 18.—*Effect of temperature upon the impact resistance (Charpy test) of leaded bronzes.*

Each plotted point represents an average of five determinations.
Compositions given in Table 3.

table 3. Alloy B-21-2 had considerably higher resistance to deformation at all temperatures than the other alloys and it is noteworthy
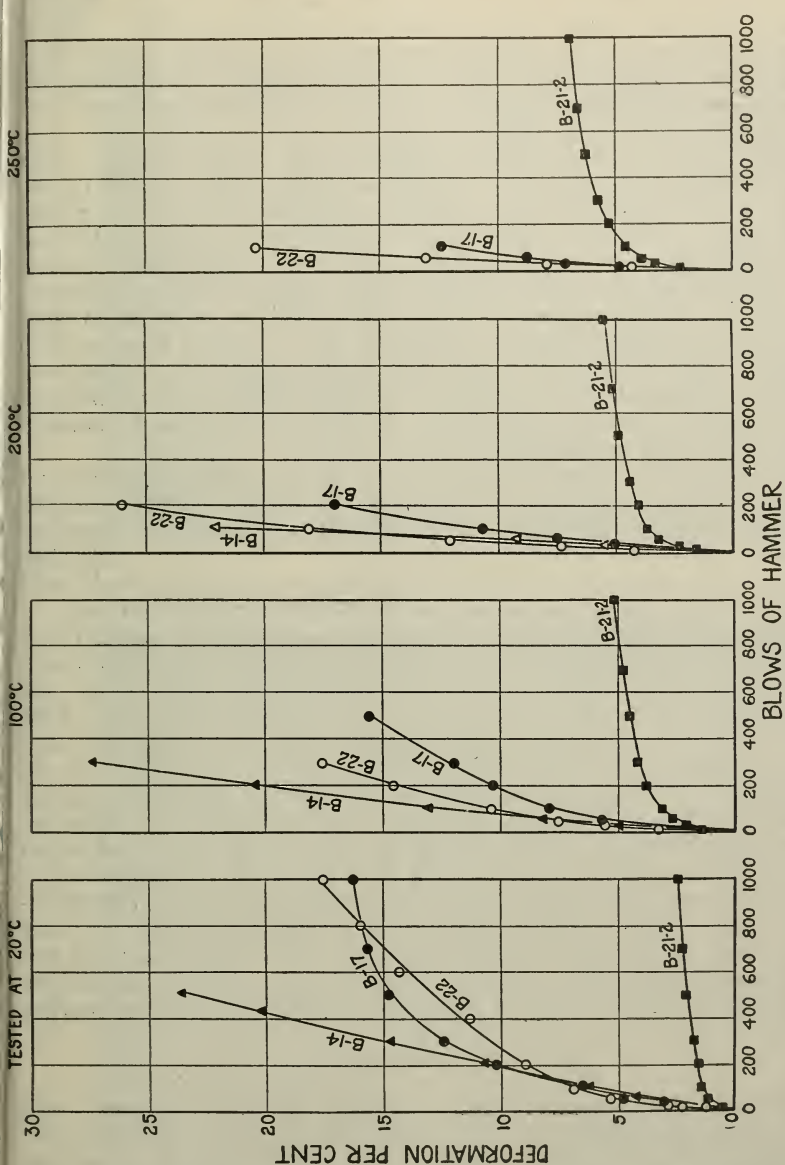

FIGURE 19.—*Pounding tests: relation at different temperatures of deformation to number of blows of hammer weighing 2 pounds and falling a distance of 2 inches.* Energy absorbed by a specimen for each bowl of hammer was approximately 0.33 foot-pounds. Compositions given in Table 3.

Each plotted point represents an average of two determinations.

that the rate of deformation of this alloy as shown in figure 19 was rather uniform from 100° to 250° C. (212° to 490° F.), inclusive.

IV. SERVICE TESTS

Two sets of connecting rod and main bearings, to fit the Wright type J-5 airplane engine were prepared for service tests.[15] These bearings were made of an alloy prepared to be the same as alloy B-21-2 (table 3), and were backed by steel shells. Chemical analysis of a sample of the bronze taken from a finished bearing indicated that the lead content was 33.5 percent.[16]

Service tests of these bearings were made at Wright Field. The bearings were run in a model V-1570 engine operated at 2,400 r.p.m. and developing 600 brake horsepower. The oil pressure was maintained at 75 pounds per square inch. The operating temperature of the oil was about 150° F. The engine appeared to be operating satisfactorily when No. 5 connecting rod broke, after running 68½ hours, due to failure of the connecting-rod bearing. A report from Wright Field indicated that there was a serious lack of bond between the bearing metal and the steel back in a number of the connecting-rod bearings and that the main bearings after the 68½ hours' run were in about the same condition ordinarily found in copper-lead bearings used under similar conditions.

A metallographic examination was made of several bearings removed from the engine after the test run and of some unused bearings, all of which had been prepared from material of practically identical composition and by the same manufacturer. The lead in both the used and unused main bearings was dispersed as rather small, well distributed particles in the copper matrix as shown in figure 20 (*a*). The structure of both the used and unused main bearings, made of an alloy of composition similar to alloy B-21-2 (table 3) was that which was characteristic of the specimens of this alloy prepared in the laboratory and upon which all the laboratory tests were made. This structure is the one which it is believed should be obtained and obviously can be secured in commercial bearings. The structures of the connecting-rod bearings were, however, quite different. The lead in several of these bearings was found to be segregated often as streaks, approximately perpendicular to the bearing face, and equal in length to the entire thickness of the bearing metal. The "streaky" or columnar structure of the lead is shown in figure 20 (*b*). The structure existing in the connecting rod bearings is believed to have resulted from factors in the manufacturing process which have not yet been sufficiently studied to perimt exact control. These conditions are believed to have been in a large measure the cause of the bearing failure.

V. SUMMARY

A series of copper-lead alloys, containing 35 to 50 percent lead together with small additions of several other elements, was prepared as pilot test castings. This was the preliminary step in an investigation having for its purpose the development of leaded bronzes of high lead content from which the tin and antimony ordinarily used as dis-

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[15] See footnote 8, p. 597.
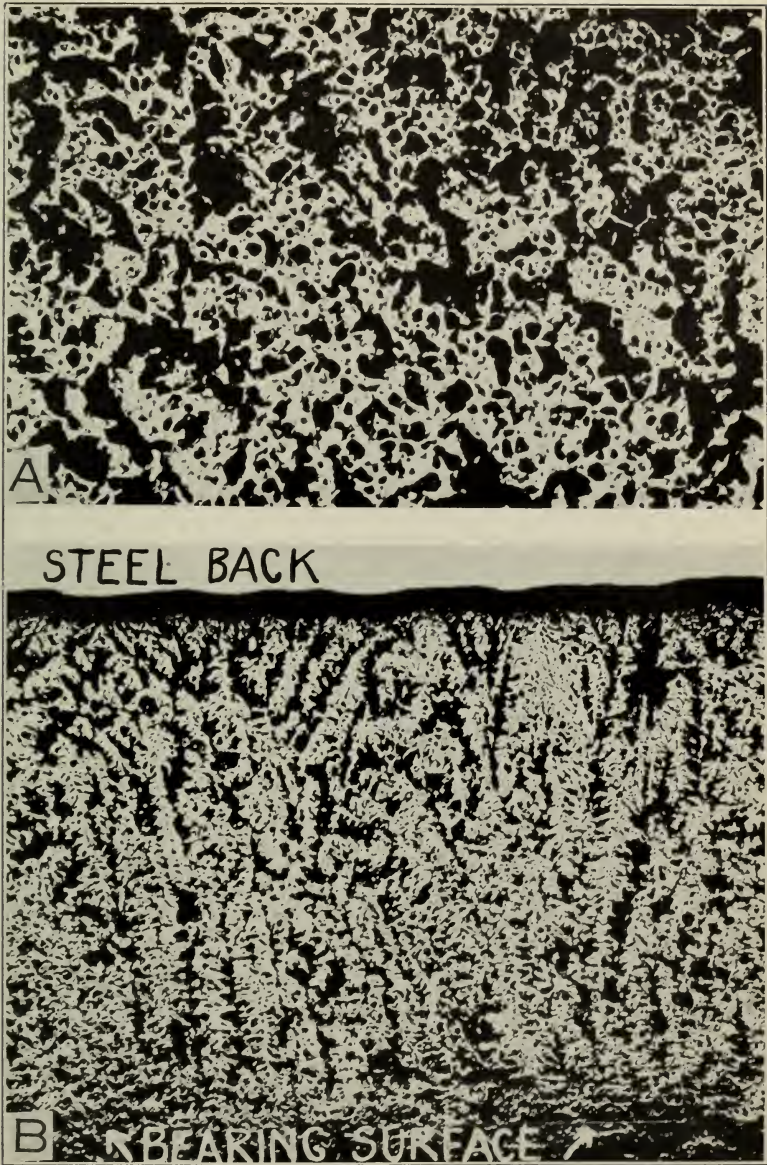[16] Analysis made by J. A. Scherrer, Bureau of Standards.

Figure 20.—*Microstructures of cross sections of bronze linings of airplane main and connecting rod bearings made of leaded bronze similar to alloy B-21-2 (Table 3).*

The lead is represented by the dark areas. ✕ 60. *A*, Main bearing. *B*, Connecting rod bearing.

persing and distributing agents for the lead were eliminated. The microstructures of these alloys were studied to determine the effect of the various additions on the dispersion and distribution of the lead particles throughout the copper-base matrix. The mechanical properties, such as resistance to wear, to impact (Charpy), to pounding (repeated impact), and strength in compression, which are believed to be of significance in the use of this type of alloy as bearings, were determined in comparison with those of similar commercially available alloys. Service tests were made on a set of connecting rod and main bearings for use in airplane engines. These bearings were prepared in a commercial plant from a leaded bronze containing about 35 percent lead, 0.4 percent sulphur, 1.5 percent silicon-zirconium alloy, and remainder copper, and developed during this study.

1. Individual additions of barium, calcium, zirconium, or sulphur to leaded bronzes showed promise in aiding in the prevention of segregation of the lead under the casting conditions used.

2. A leaded bronze free of both tin and antimony and containing sulphur and silicon-zirconium alloy was developed. The maximum lead content obtainable in this alloy was about 45 percent. The lead in the alloy was highly dispersed and uniformly distributed. Microstructural examination and mechanical tests indicated that the optimum additions to a high-lead bronze containing sulphur and silicon-zirconium alloy should be 0.4 percent sulphur and 1.5 percent silicon-zirconium alloy.

3. Laboratory wear tests on the sulphur-silicon-zirconium-treated leaded bronze and on a series of commercially available leaded bronzes of high lead content indicated that the wear resistance of the former was equal or superior to any of the commercial alloys tested, some of which contained up to 6 percent tin.

4. The results indicate that the compression strength of the new alloy, developed during this study, was as high as that of a commercial leaded bronze containing 10 percent less lead. This commercial alloy, however, showed higher impact resistance probably on account of the lower lead content, but the difference decreased materially as the temperature of test was increased.

5. The resistance to deformation under pounding for the leaded bronze, containing 0.4 percent sulphur and 1.5 percent silicon-zirconium alloy, was not materially affected by temperature, particularly between 100° to 250° C. (212° to 490° F.).

6. The structure and general physical appearance of bearings prepared of the sulphur-silicon-zirconium-treated leaded bronze for service tests indicate that this material can be readily handled commercially in the manufacture of bearings.

7. The main bearings removed from an airplane engine, which had been operated for 68½ hours, were in about the same condition as ordinarily found in copper-lead bearings used under the same conditions. Some of the connecting-rod bearings used in this engine failed. A metallographic examination of these bearings showed the lead to be segregated often as streaks equal in length to the entire thickness of the layer of bearing metal. These conditions are believed to have been in a large measure the cause of the bearing failures.

VI. ACKNOWLEDGMENTS

WASHINGTON, February 1, 1933.